ADAPTIVE BUILDING ENVELOPE: Performative Water-filled ETFE Cushions

Designing a multi-functional building envelope as an architectural fa ade, environmental interface and Solar Collector is a multi-objective exploration that should be solved through an Integrated Design Strategy

Deliver justice for impacted people

prepared by:

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Transsolar academy

Upon receiving my Bachelor's degree in Civil Engineering, I graduated with a Master's degree in Architectural Technology; with a focus on multidisciplinary approaches in the design process of the building envelope. In this new landscape, the design process of multifunctional elements is focused on the combination of form finding, material selection and assessment of the environmental behaviors.

2002 2008 2015

Civil Engineering B.S. | Architectural Technology M.S. | Traveled to

Transsolar academy

weeping Lake

Lake Urmia is a UNESCO Biosphere Reserve



While celebrated as precious source of inspiration in traditional architecture, the lack of multidisciplinary approach in Iran restricts any modern interpretation of these solutions toward a new design. Most of the scholars and architects in Iran only operate computers for the purpose of drafting or rendering. Yet, computational design shifts the boundaries of disciplinary roles and opens up the possibility for the emergence of a performance-oriented design. In this approach, the design can be considered as a process of multi-objective exploration that is driven by some desired performances (aesthetic, structural and environmental). In Iran, those of us who consider the practice of design with new digital tools as a collaboration of architects and engineers remain on the fringes.

ARCHITECTURE WITH ARCHITECTS

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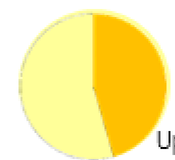
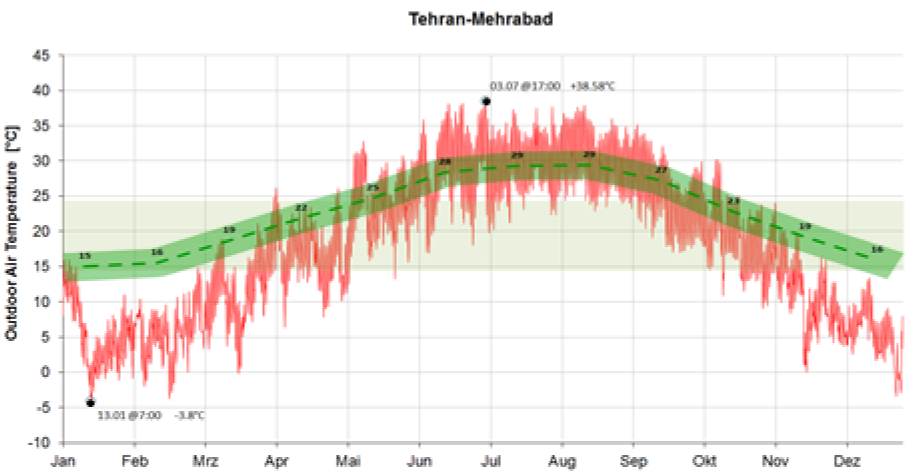
Before starting my Ph.D. studies in Iran, I researched vernacular architecture as solutions for climatic design and passive strategies. In contrast to modern strategies, the traditional architecture offered simple yet holistic solutions to complex problems. In some of the Iranian vernacular architecture, the harsh climate and inhospitable environment is most effectively tempered by the use of gentle tectonic ornamentations such as Palekanes (Mashrabiyes), Orosi windows, Wind Catchers, and so on.

Weather Analysis

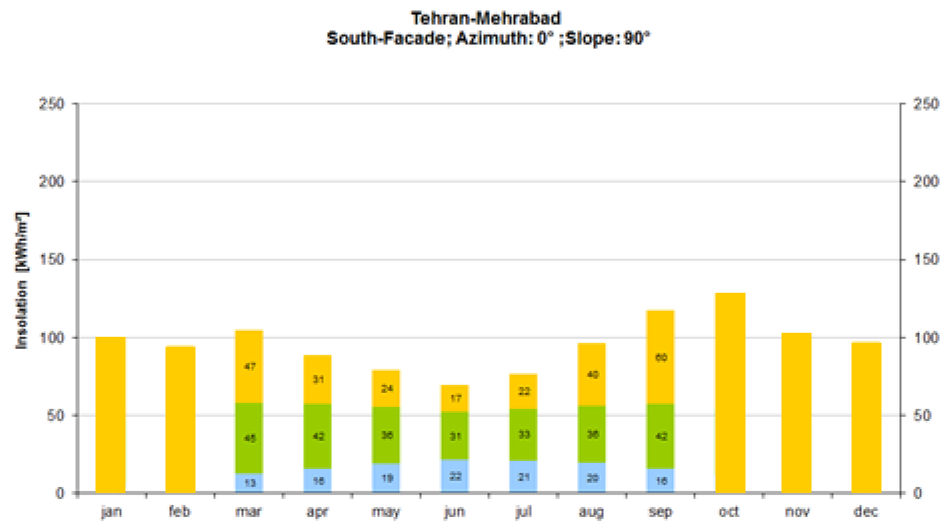
Location : Iran, Tehran



Up to 3660 sunny hours a year



Thermal Comfort Range: Adaptive Comfort Curve (Heydari, 2008)



Total Insolation (Jan, Feb, Oct, Nov, Dec) on South Facade : 319 kWh/m2

total 1156 kWh/m²/a ■ Ground Reflection 170 kWh/m²/a ■ Diffuse Radiation 461 kWh/m²/a ■ Beam Radiation 525 kWh/m²/a

Source Weatherfile: Tehran-Mehrabad 407540 (ITMY)

Passive Design Strategies:

Natural Daylighting: Up to 3660 hours

Passive Heating

Direct Solar Gain

High Thermal Mass + night Flushed

Trombe Wall and Water Walls

Passive Cooling

Shading for Solar Heat Gain

Natural Ventilation

Humidification and Direct Evaporating Cooling

Earth Cooling (Conductive Cooling)

Tehrmal Comfort Range:

18° - 21° (Iran Meteorological Organization)

Adaptive Comfort Curve (Dr. Sh. Heydari)

Concept

Multifunctional Adaptive Facade

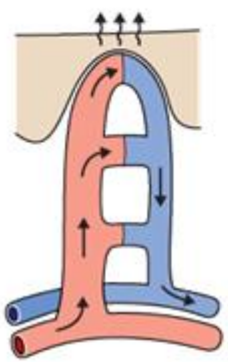
Multifunctional:

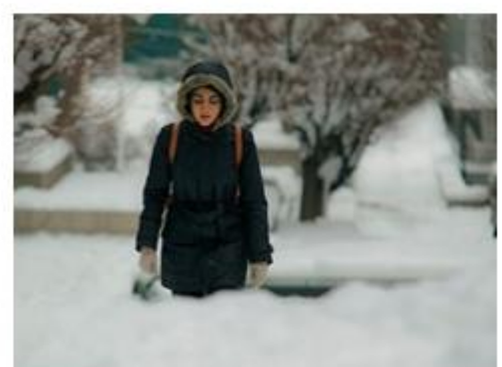
Designing a building envelope as an **architectural** façade, **thermal** barrier and load bearing **structural**

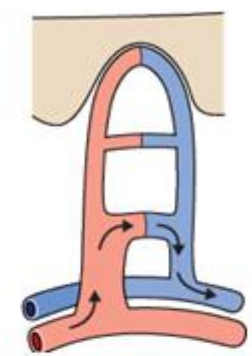
Adaptive:

Interacting dynamically with the environment

Water as building's blood Transfer the amount of heat energy from the building core to the surface or vice versa.







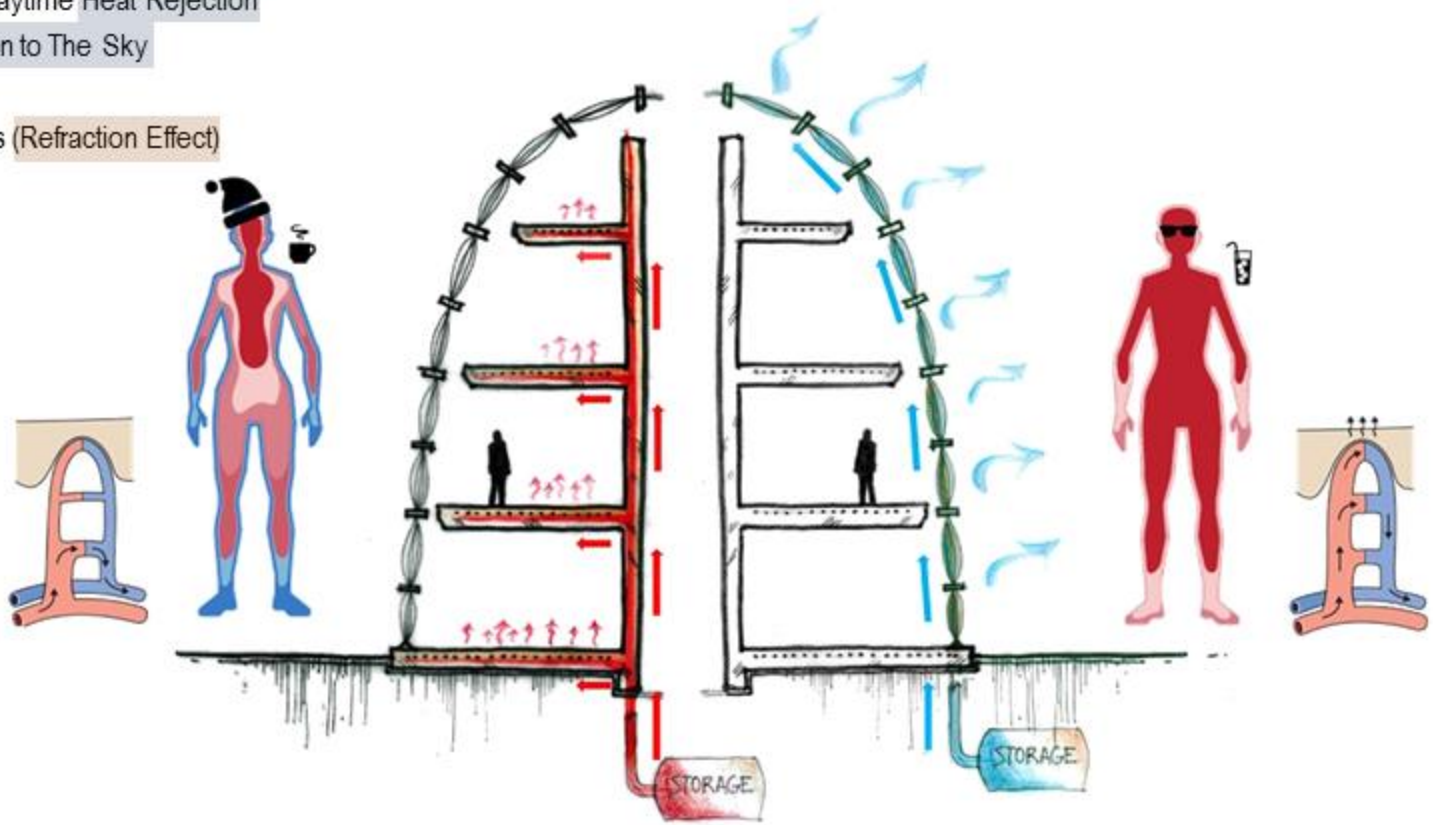
Blood circulation and its velocity changes during the cold and hot stresses is controlled by a feedback system in the hypothalamus; the temperature-regulating center of the brain. When cold, the hairs are raised by small muscles to trap a layer of air near the skin goose bumps or fluffing in birds. Decreasing the convection the trapped air as an insulator helps to keep heat in. blood is also kept away from the surface by vasoconstriction. In hot, the blood vessels leading to the skin capillaries dilate, known as vasodilation. This allows lots of blood to flow near the surface and heat is lost through the skin by convection and radiation. All these mechanisms are parts of a normal behavior in warm-blooded animals to control their body temperature (M Lauster, 2009).

Concept

Multifunctional Adaptive Facade

Adaptive Envelope Functions:

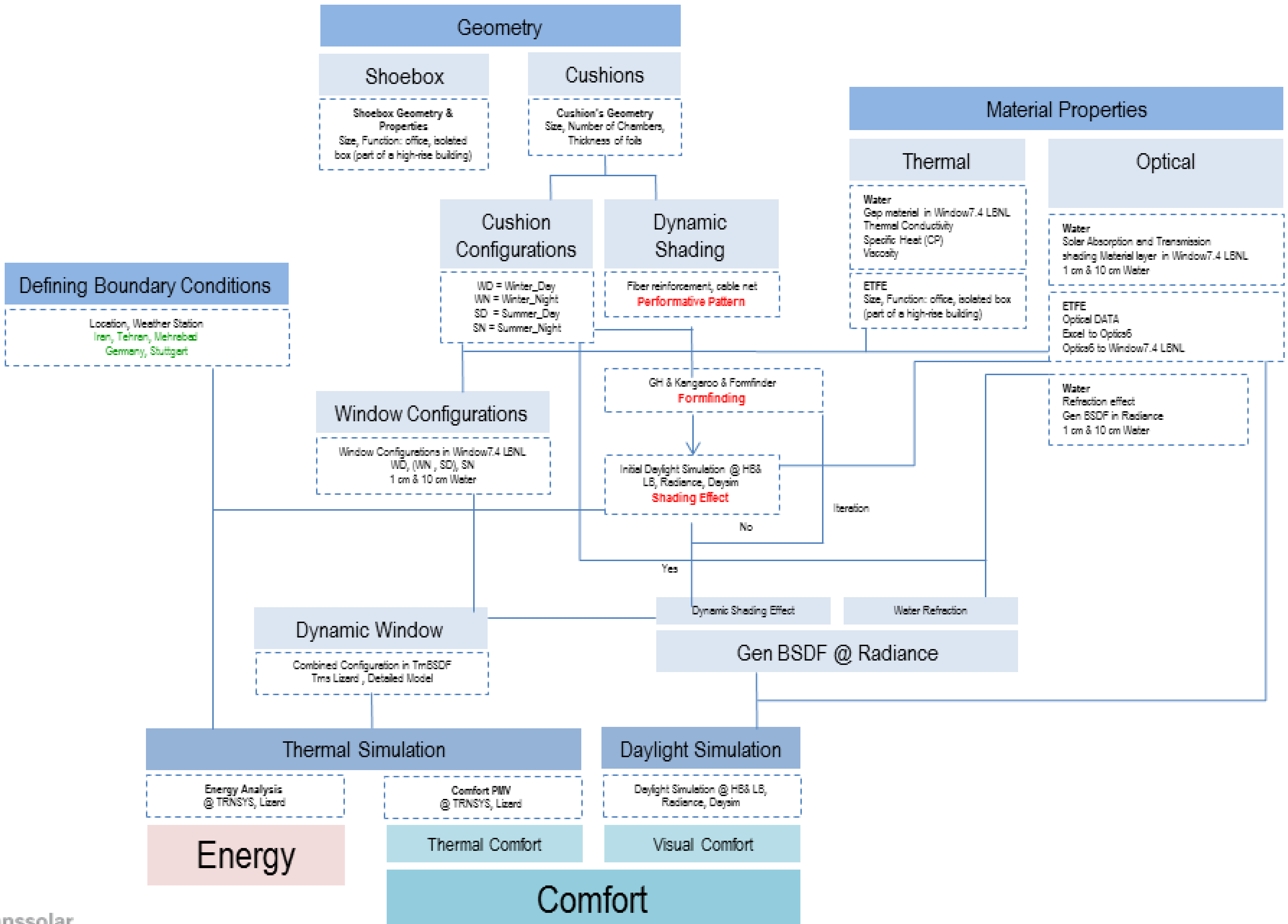
1. Transparent Solar Heat Collector
2. Dynamic Shading and Daytime Heat Rejection
3. Night time Heat Rejection to The Sky
4. Supply Useful Daylight
5. Shading Without Shades (Refraction Effect)



WATER as BLOOD

Inspired by the blood circulation responding to heat and cold stress, in a comprehensive approach, every multi-layer cushion of this envelope has a great possibility of interacting dynamically to the environment. the cushion as the live responsive skin is able to imitate birds' fluffing in cold winter to gain heat and keep it inside the vital organs and lose more heat by radiation or convection transferring outer surface like mammals' behavior in hot summer. Thermal and visual properties of the components can be regulated by a controlling system that adjusts to the direction and the amount of heat flow, based on the variable climatic conditions. In addition to activating the glazing with circulating water in water bladder to behave dynamically for daylighting and solar heat gaining; in order to increasing the responsivity of the system, the building's body is also activated as part of the hydronic system. The thermal mass in slabs, walls and foundations are enlivened to connect thermally with occupants and ambient air and soil. Accordingly, the dynamic solar envelope in synergy with building active systems is capable of transferring the amount of heat from the building core to the surface or vice versa.

Methodology

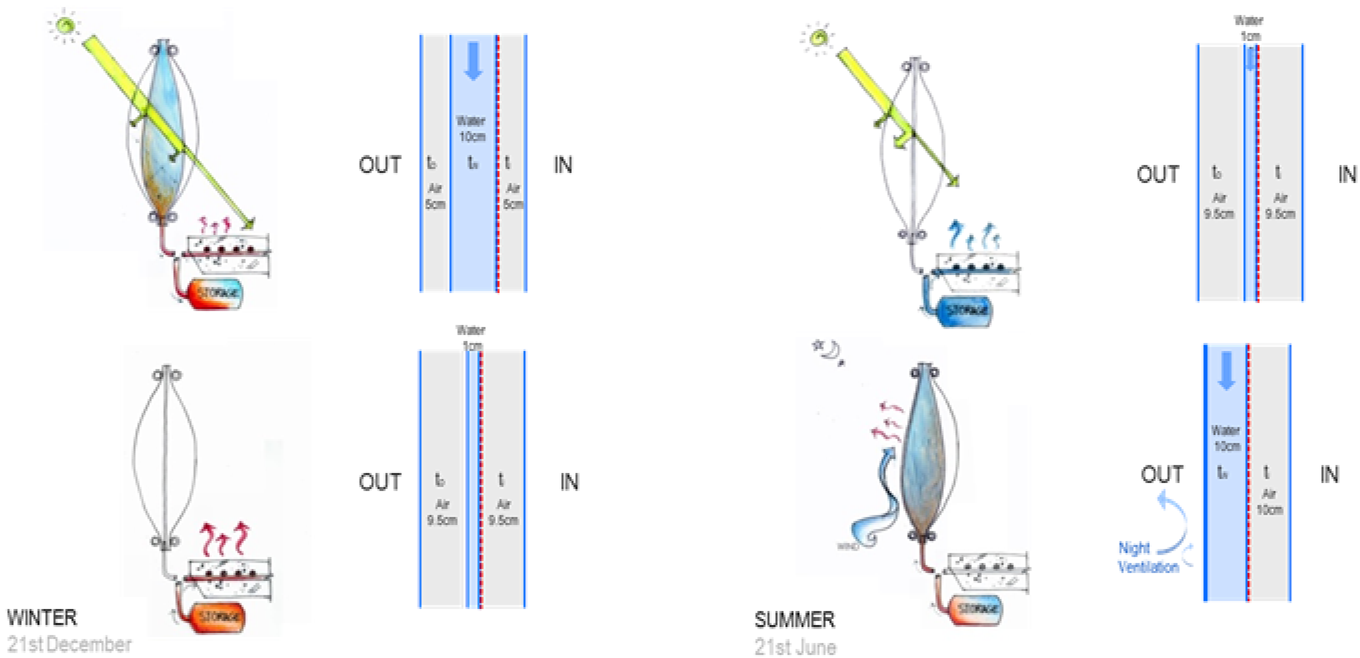


LBNL WINDOW 7.4 AND RADIANCE

The simplified models for different configurations are set up in LBNL Windows 7.4. for evaluating the thermal and optical behaviors. In order to, the optical properties of 0.25 mm (0.01 in) of clear ETFE foils (Nowoflon ET 6235 Z 250) with 0.898 solar and 0.886 visible lights Transmissivity is defined in Optics 6 and exported to LBNL Window as a glazing and as a Glass Radiance material with BRTDfunc for the daylight simulation with Daysim via Honeybee. The optical properties of water are defined by assigning a dielectric material in Radiance with Refraction Index of 1.33 (Segelstein, D., 2011). The thermal conductivity of water are also defined as some polynomial curves based on different temperatures (0-50 $^{\circ}$C) (32-122 $^{\circ}$F) as a new gap gas in LBNL Window Gap library.

Complex Fenestration Modeling

Simplification and Defining Water as Shading Material and Gap Gas



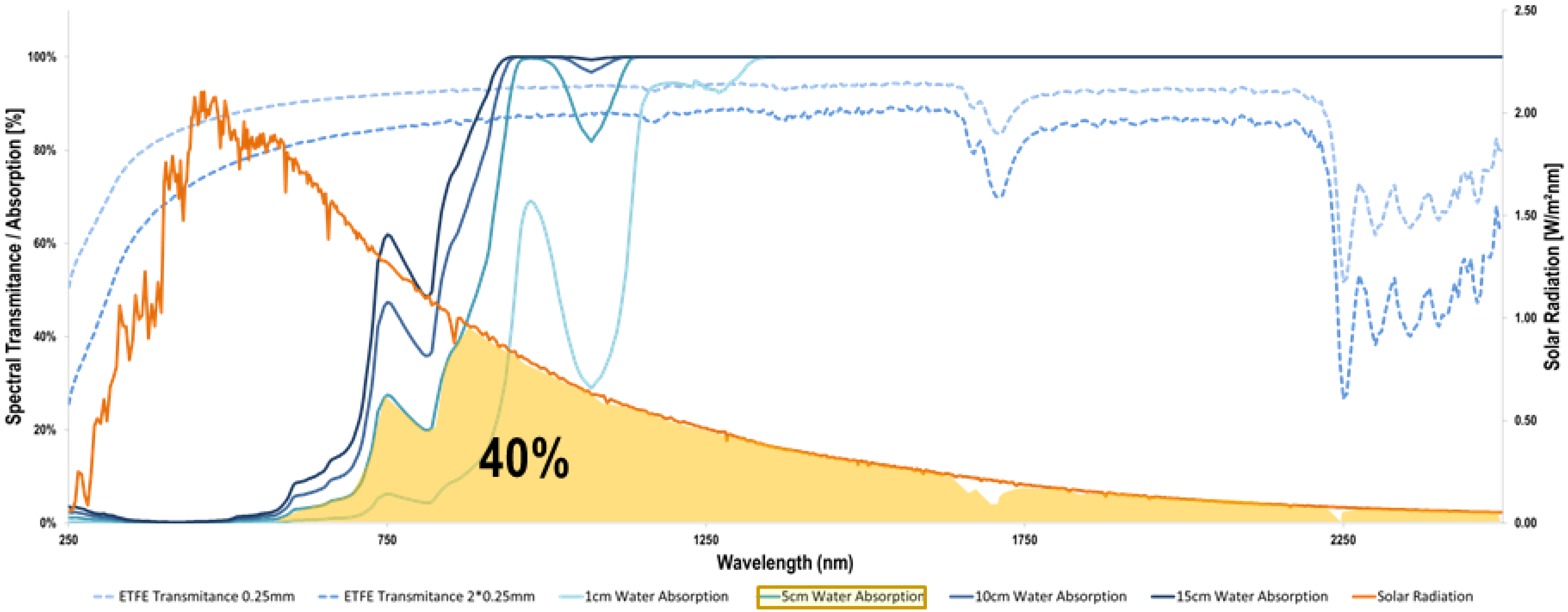
1. Defining optical properties of ETFE foil and coating films — @ optics6
2. Defining solar absorption of water layer as homogeneous diffusing shade — @ LBNL windows
3. Defining thermal properties of water layer as gap gas — @ LBNL windows
4. Assembling the glazing systems and generating BSDF & .ldf — @ LBNL windows
5. Generating BSDFs based on the dielectric material and cushion geometry — @ radiance
6. Defining refraction effect of water layer as .xml as shading — @ LBNL windows
7. Generating combined BSDFs as .dat — @ TrnBSDF
8. Comparing the layer's temperature results (NFRC) — @Trnsys 18

TRNSBSDF AND TRNSYS18 (DYNAMIC THERMAL SIMULATION)

In new coming version of TRNSYS18, it is possible to apply the BSDF data for a complex fenestration system generated by LBNL Window and combine as different configurations of a detailed window for any dynamic thermal simulation. This new features provide one detailed window containing all optical and thermal information of layers and gaps, which is possible to calculate the absorbed solar radiation and temperature for each layer and gap specifically.

Spectral Solar Absorption & Transmittance

Water Layer as Smart Selective Layer

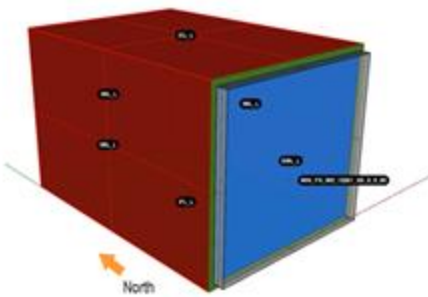


Referring to the figure, it is noticeable that depending to the thickness of water, the light absorption of water layer in visible part of spectrum (380—700nm) is negligible (0.07% to 11.41%) but the solar absorption (250-2500nm) is significant (30.33% to 48.18%) in infrared part. For example all the solar radiation with the wavelengths larger than 1125nm are absorbed by 15 cm (5.91 in) of water layer, while 5cm (1.97 in) of water layer only absorbs the solar radiation with wavelengths larger than 1230nm.

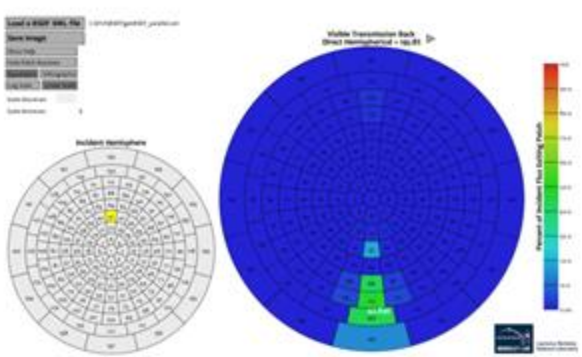
Static Daylight Simulation

BSDF Matrix_ Study the effect of water layer

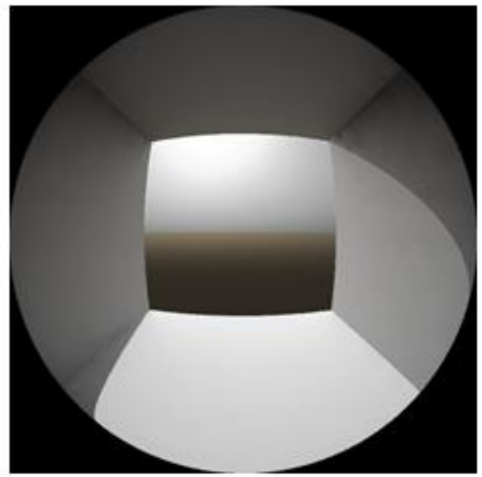
21st December

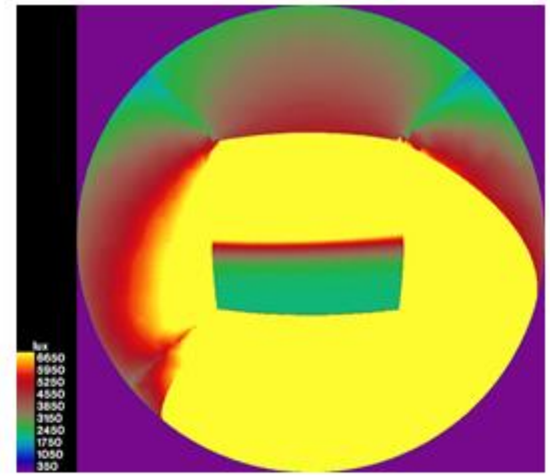


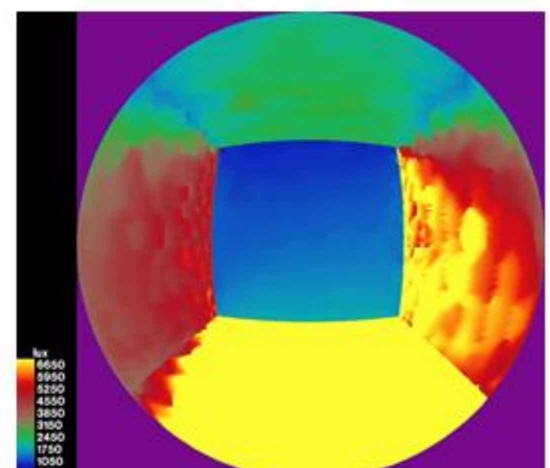
Length	5.0 m
Width	3.5 m
Height	3.0 m
Window Dimension	3.3*2.8=9.24 m²
Area	17.5 m²



Glass







Parallel Water

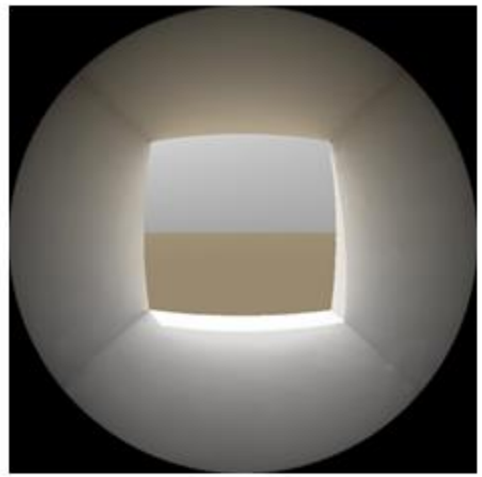
Winter Conditions: Increasing the thickness of water layer, the amount of absorbed solar radiation would be a supplement source of energy for heating. During the cold night, the exterior air layer plays the role of Night Insulation.

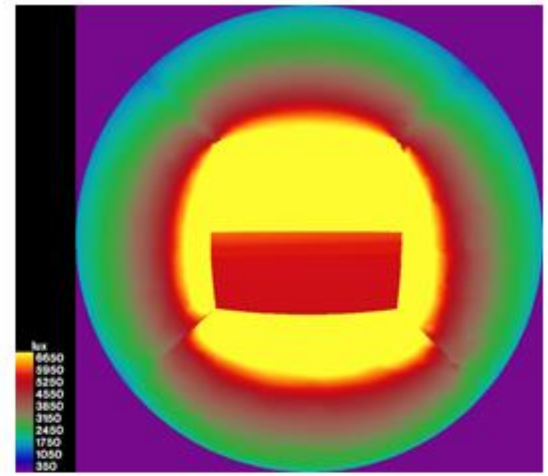
Static Daylight Simulation

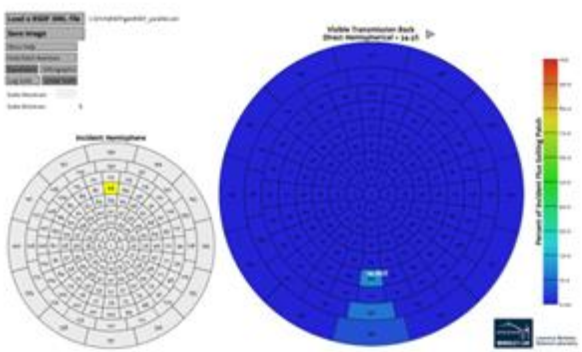
BSDF Matrix_ Study the effect of water layer

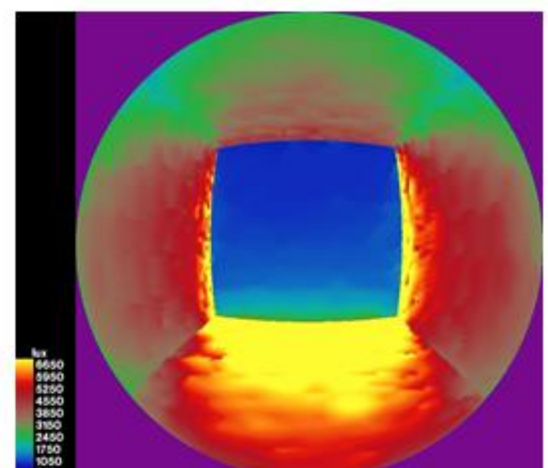
21st June

Glass









Parallel Water

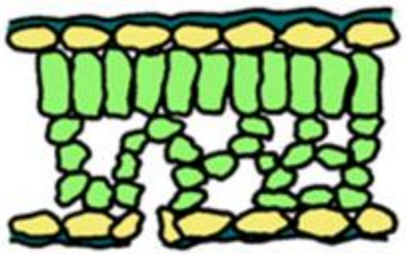
Summer Scenario: According to the absorption coefficient of water, this selective layer can gain 30-48% of solar radiation and allow more than 99-88% of the visible light spectrum to transmit through the envelope and supply sufficient daylight.

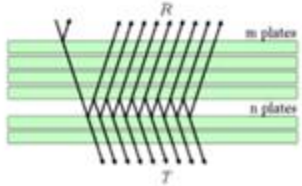
Consequently, the intelligent behavior of water layer in a combination of ETFE foil makes a high-performance selective layer with high Solar Heat Gain Coefficient and high Visible Light Transmission. This function can avoid the problem of overheating during a summer day and decrease cooling and electrical loads effectively.

The dynamic shading by different fritted pattern on ETFE foils and Diaphragm Configuration, internal refraction phenomena inside water layer and the effect of shape on more uniform distribution of light in the room are also some new interesting aspects of this study.

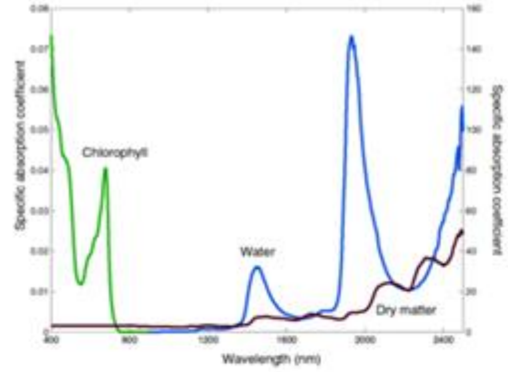
LOOK DEEP INTO NATURE

Green leaf optical properties, Dynamic shading device





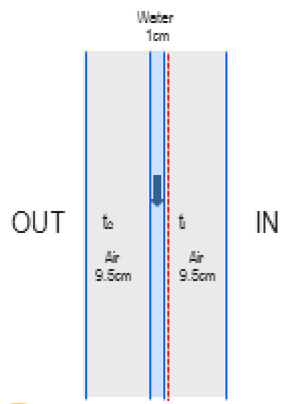
Multiple Reflection



Chlorophyll Pigment

Adaptive Performative Windows

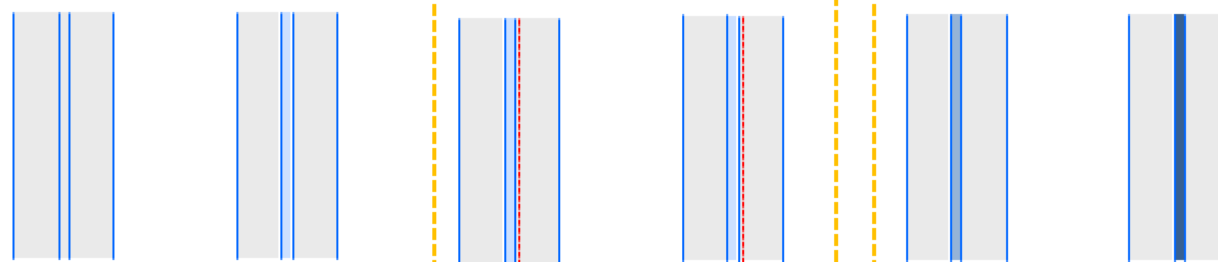
Evaluating the performance of window configurations



Glazing Collector, WinterDay

+ Reflective Coating

+ Pigment Concentration



0 SHGC : 71% T visible: 65% Clear ETFE+Air

1 SHGC : 58% T visible: 59% 1cm Pure Water

2 SHGC : 48% T visible: 48% +HeatMirror77

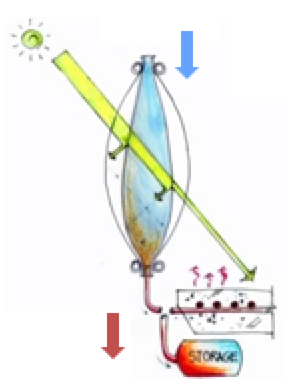
3 SHGC : 34% T visible: 30% +HeatMirror44

4 SHGC : 50% T visible: 47% +1% Concentration

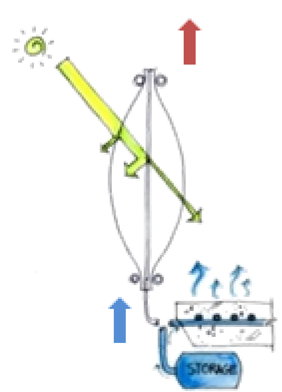
5 SHGC : 48% T visible: 40% +2% Concentration

sDA300Lux

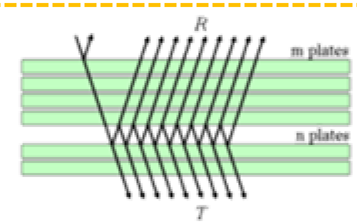
67%

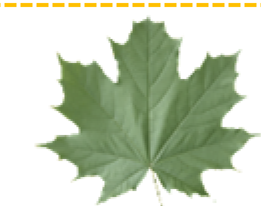


WINTER



SUMMER



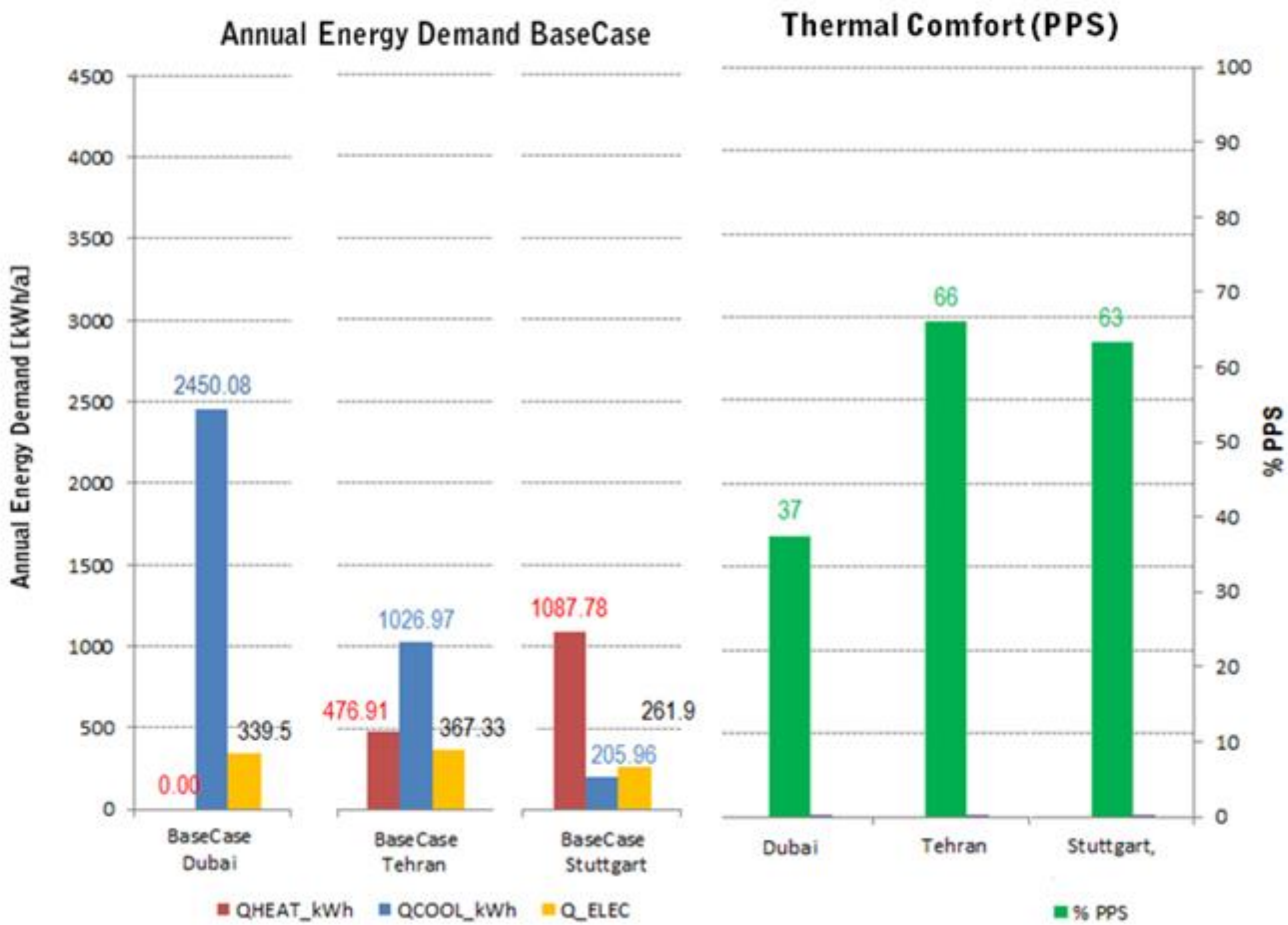


As shown in figure 8 for the comparison study, the thickness of water layer is assumed 1 cm (0.39 in). Zero configuration is a conventional multi-layer ETFE cushion with 4 foils and 0.25mm (0.01 in) thickness and three cavities and the main configuration (configuration 1) is a multi-layer ETFE cushion, which the middle cavity is filled with 1cm (0.39 in) of pure water. The optical properties of systems for other four configurations (configurations 2 to 5) are adjusted by applying Reflective Coatings (HeatMirror77 and HeatMirror44 for configurations 2 and 3), and dyed water with pigment (1% and 2% of concentration for configurations 4 and 5).

Dynamic Thermal Simulation

Dubai, Tehran and Stuttgart Office Building_ Base Case

Double glazing window, ID13002, Uvalue= 1.1, Gvalue= 0.6
70% moveable external shading

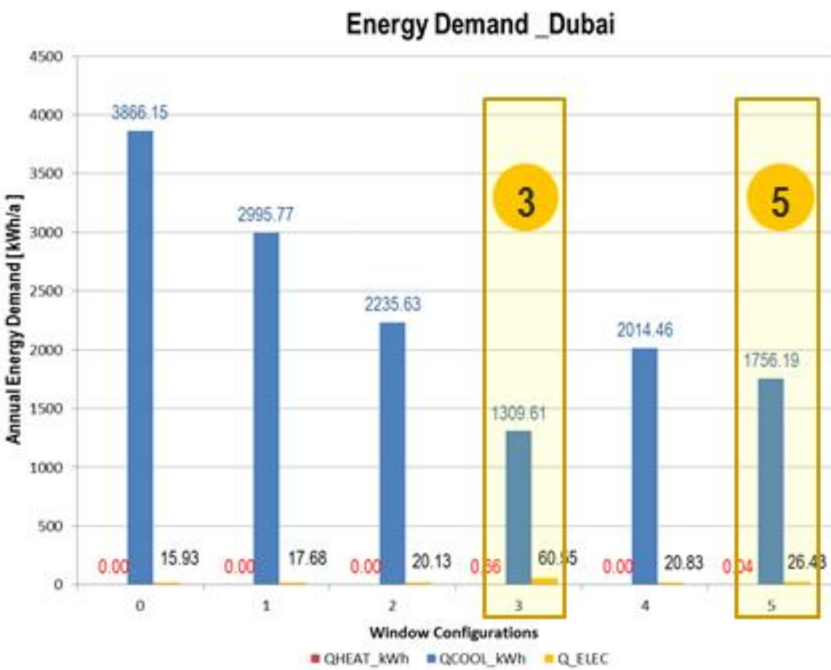


Assessing the potential of the different configurations of system, three base cases are modeled with the same properties but a standard double glazing window. All the thermal properties for the external and internal walls, ceiling and floor for all the configurations and base case model are kept the same. Window wall ratio is 90% and the window property for base case model is a double glazing window (ID13002) with U-value of 1.1 W/m^{2}K (0.19 Btu/(hr ft^2 $^\circ$F)) and the G-value of 60% with 70% reduction due to motorized moveable external shading. In figure 7, the performances of standard base case buildings in Dubai, Tehran and Stuttgart are shown.in this figure (figure 7), the amount of annual energy demand [kWh/a] for heating, cooling and artificial light is compared with thermal comfort representing by PPS [%] (Predicted Percentage of Satisfied).

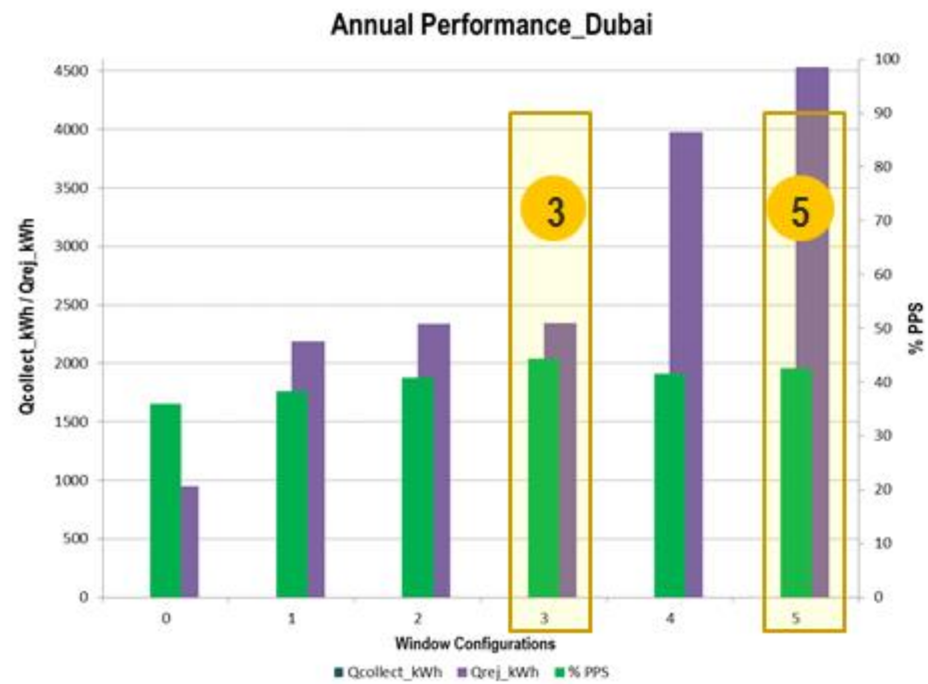
Adaptive Performative Windows

Selecting the most performative windows, Dubai

As shown in Annual energy demands and annual performances diagrams (Figure 10-12), the performance of each configuration is highly dependent to the climate conditions. For example in a hot climate like Dubai, the system is only worked for cooling purpose. In this case, performance of configurations 1 to 3 is more or less the same; but using a reflective film is reducing the cooling demand significantly. While providing enough useful daylight for the space, configurations 4 and 5 can also reduce the cooling demand.



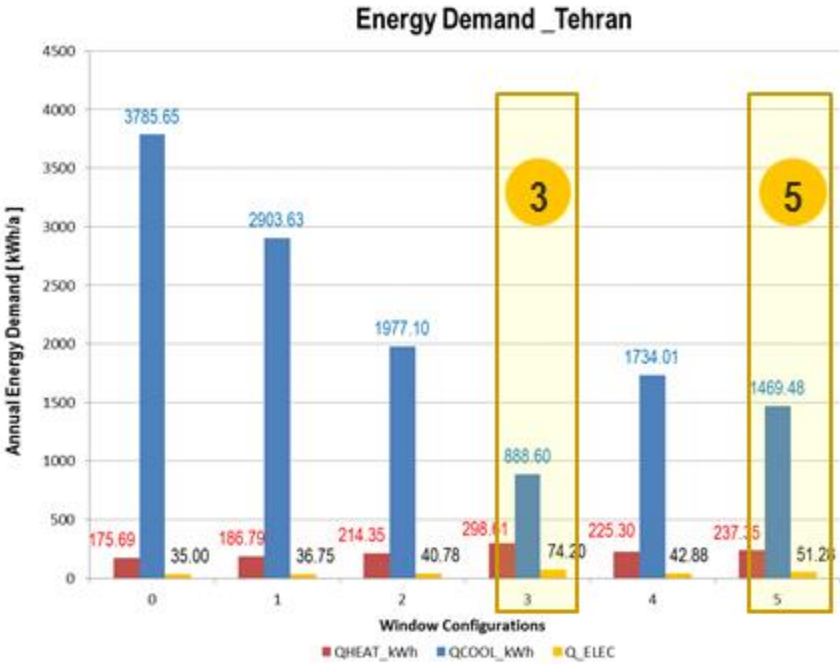
Thermal Comfort and Heat Collecting & Rejecting Potential
Heat Collecting efficiency



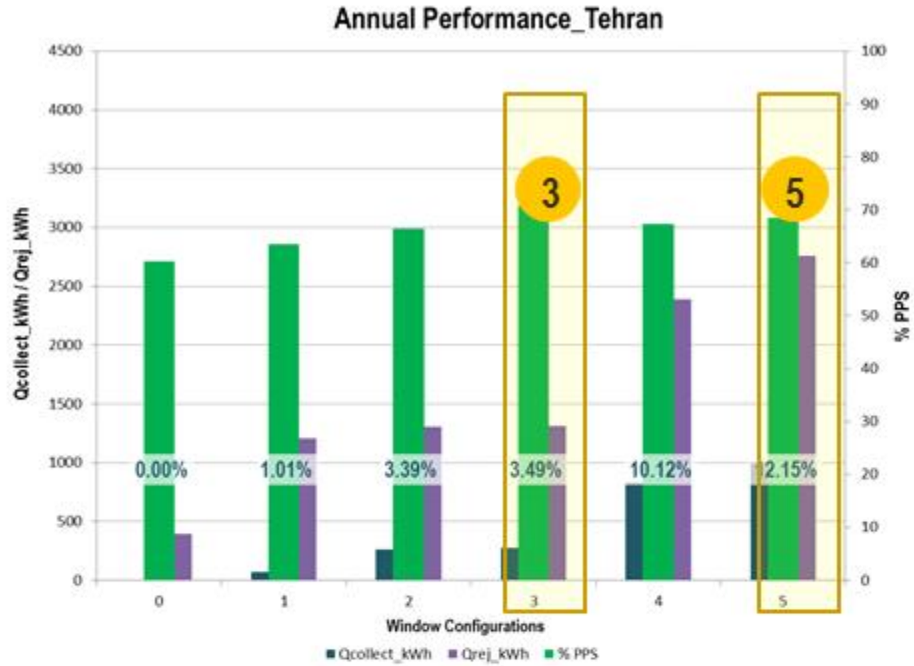
Annual Energy Performance

Adaptive Performative Windows

Selecting the most performative windows, Tehran



Thermal Comfort and Heat Collecting & Rejecting Potential
Heat Collecting efficiency



Annual Energy Performance

In terms of providing useful daylight in the space, the annual daylight simulation for the worst configuration (configuration 3, with 30% T_{vis}) has been studied with sDA parameter. Spatial Daylight Autonomy (sDA) describes how much of a space receives sufficient daylight. Specifically, for Tehran, it describes the 67% of floor area receives at least 300 lux for at least 50% of the annual occupied hours. This performance has a great impact on reducing the electricity demand for artificial light in comparison to the base cases with automated shadings.

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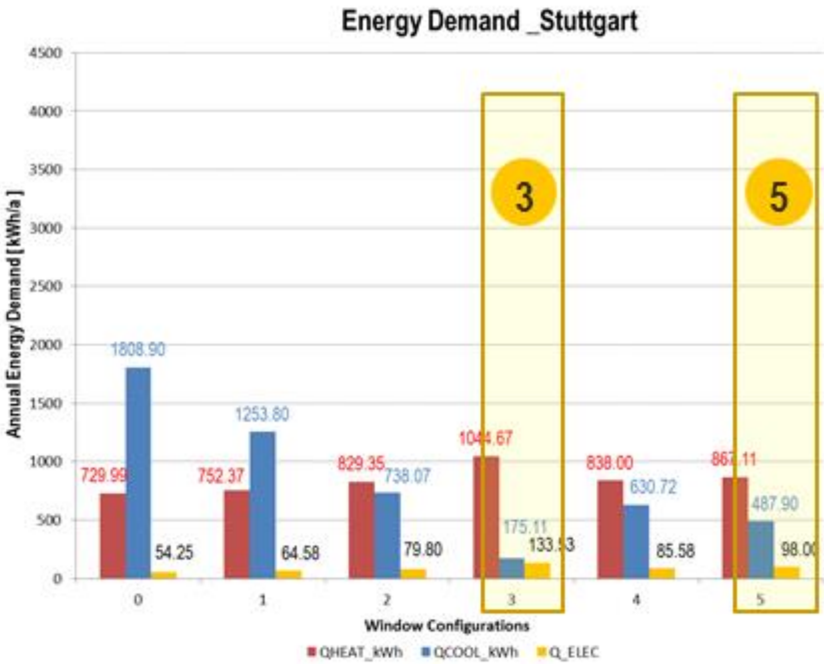
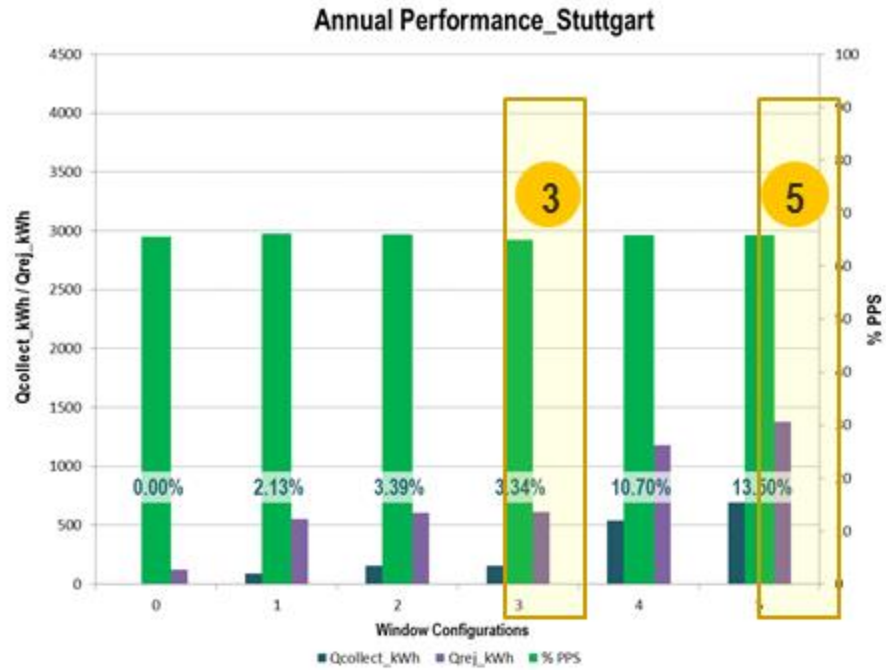
Adaptive Performative Windows

Selecting the most performative windows, Stuttgart

The results also show that the increasing of shading effect due to reflective films on third layer or adding color to water can rise the efficiency of the fa ade component by gaining more heat in water during winter and avoiding risk of overheating in summer.



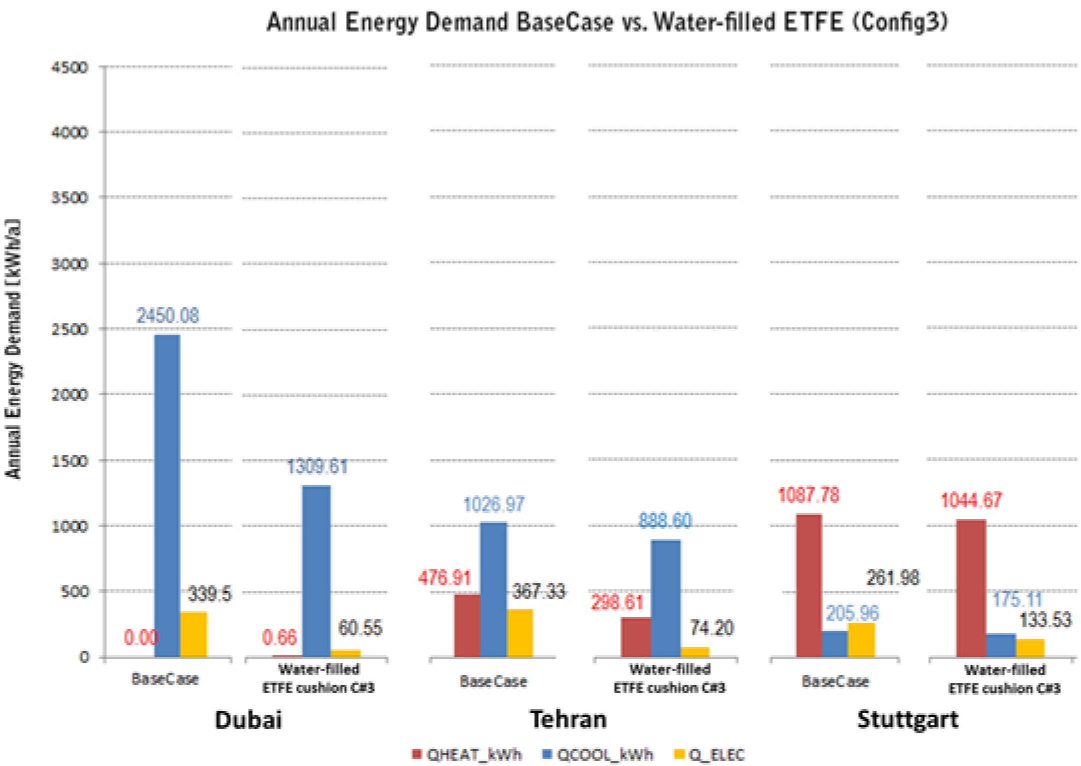
Thermal Comfort and Heat Collecting & Rejecting Potential
Heat Collecting efficiency



Annual Energy Performance

Dynamic Thermal Simulation

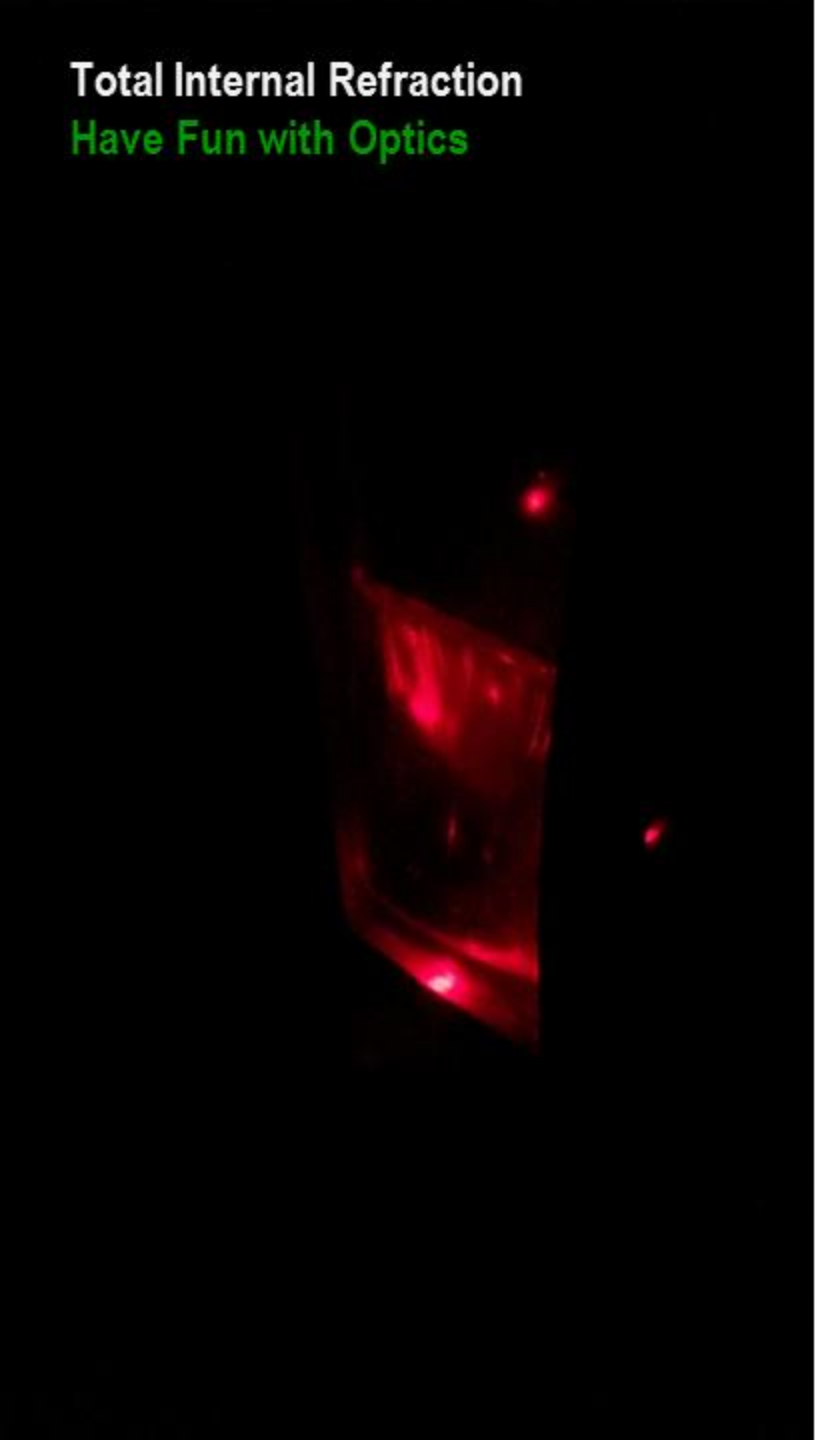
Comparing Base Cases with Adaptive Facade

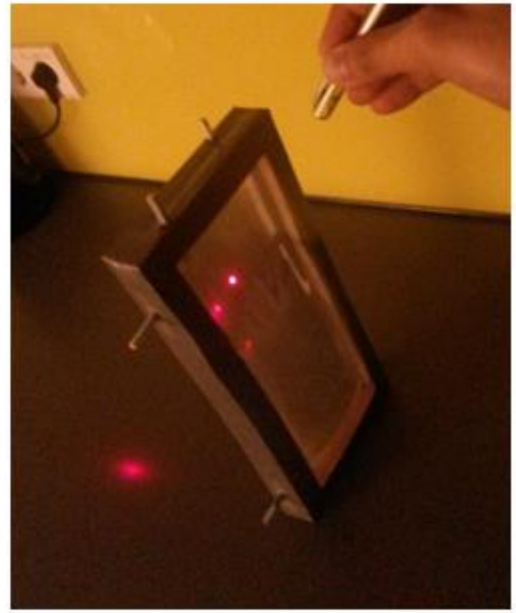


The proposed façade component as a transparent collector allows some of the mentioned potentials for a south oriented window in different climates:

- Reduction in heating demand and harvesting solar heat (Tehran: 100% and Stuttgart: 55%)
- Reduction in cooling demand: (Dubai: 1140, Tehran: 137 and Stuttgart: 30 kWh/a (3889.8, 467.5, 102.4 KBTU/a)
  - Decreasing SHGC by absorbing solar radiation while it is almost transparent for visible light
  - Heat Rejection during summer night by radiation to the cold sky
- Maximizing the daylight utilization and significant reduction in electricity demand. (Dubai: 279, Tehran: 293 and Stuttgart: 128 kWh/a (952, 999.8, 436.8 KBTU/a)
- In Addition to aesthetic advantages of using different colors for water which can control the absorption and shading effect
- Controlling the direct sunlight by using total internal reflection inside the water layer (work in progress)

The full potential of the dynamic water-filled ETFE cushion and the controlling mechanism of "Building's Blood Circulation" can only be achieved after evaluating different configurations for each climate through dynamic simulation and find the most appropriate controlling strategy. However, at this stage of the research none of the combined dynamic control strategies has been assessed completely to improve the performance. The results of configuration 3 are comparing with the base cases in figure 13, for three different climates.





shading without shades:

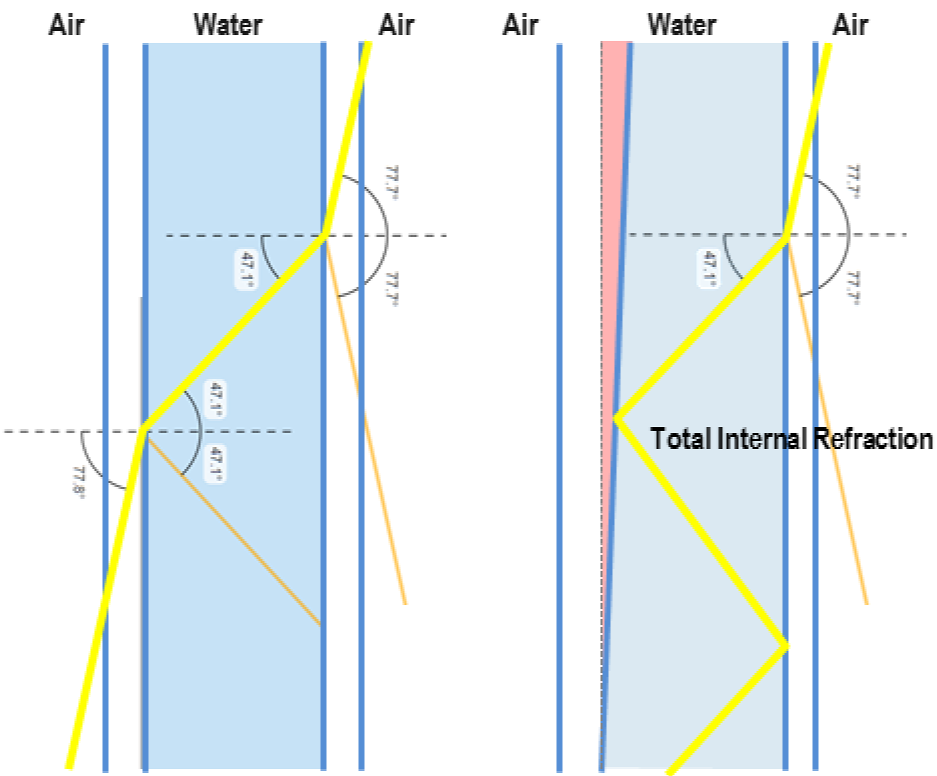
the idea of redirecting light by water layer
and the effect of shape to adjust the sunlight distribution effectively

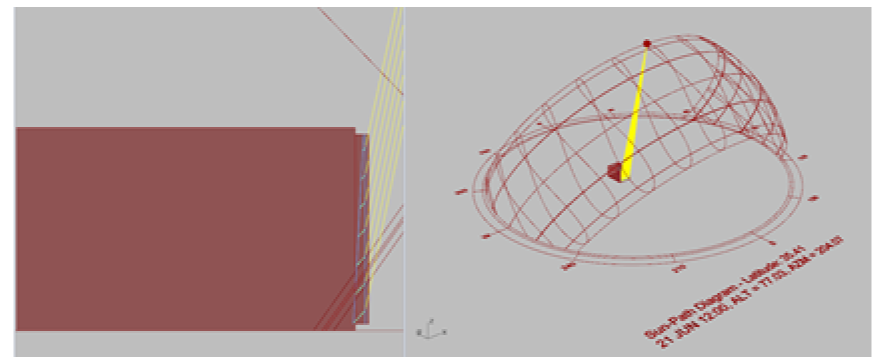
Testing mockup, left: high angle light transmits through the empty cushion.
Right: high angle light is blocked and refracted inside the water filled multi-layer cushion.

Testing mockup, adaptive light distribution in the water filled multi-layer cushion
by controlling the air pressure in outer air cavity.

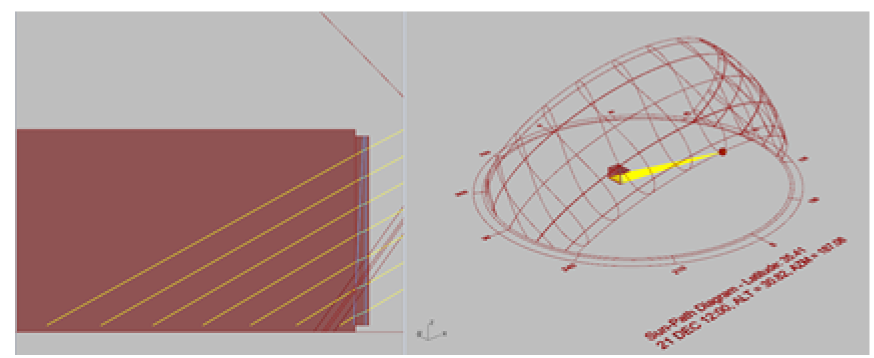
Total Internal Refraction

Have Fun with Optics





Summer solar radiation is blocked



Winter solar radiation is transmitted

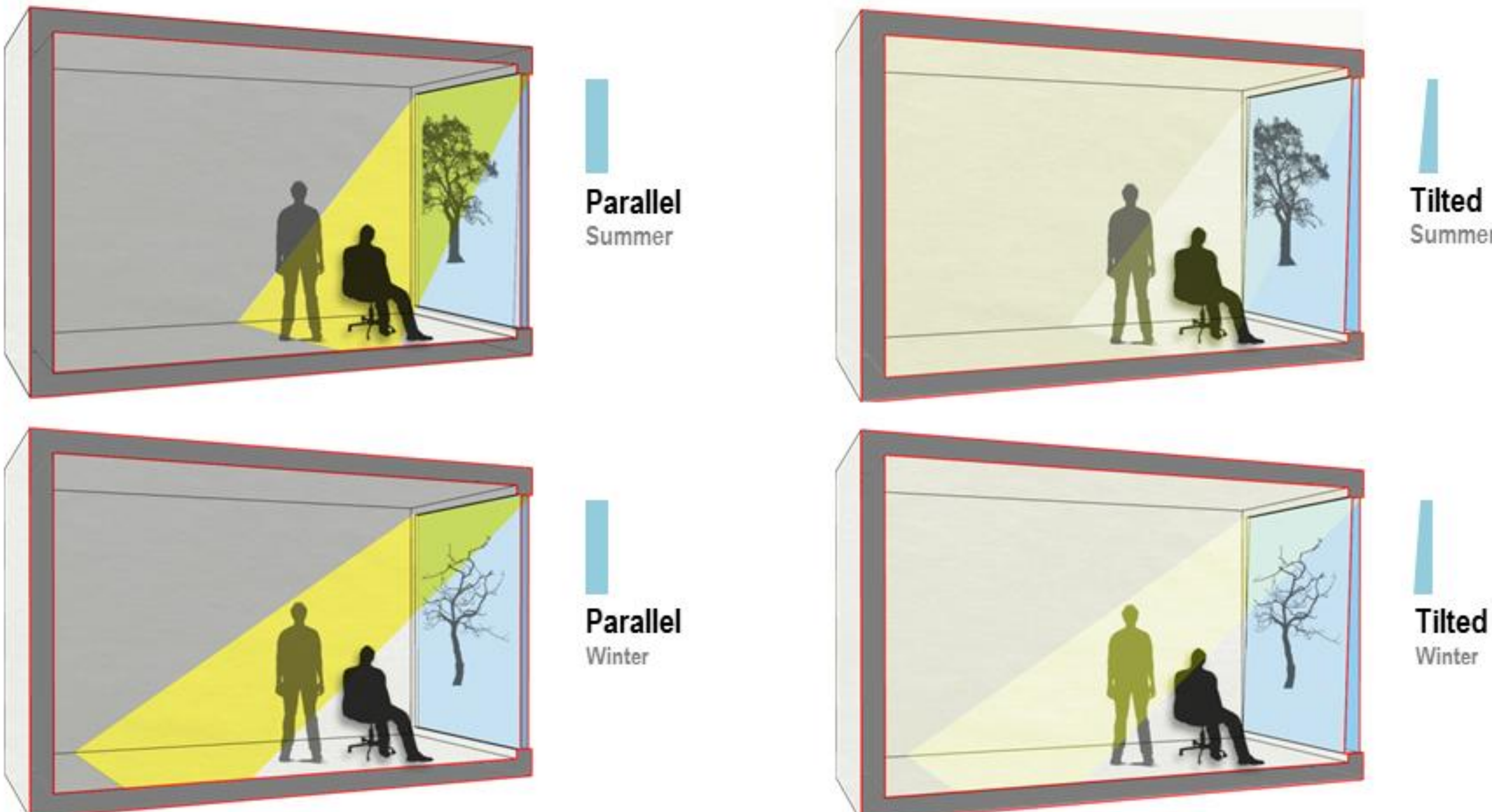
Play

Internal refraction inside the water cavity due to the tilted inner pane And blocking the incident radiation during summer time (21st June, Tehran)

Grasshopper definition and geometrical study: In order to study the proper geometry and figure out the appropriate rotating angle for different latitudes, a grasshopper definition has been developed to calculate the angle for any desire location and period of time. Some of the results are shown in the below table (Table 1).

Shading without Shader

Controlling the light distribution through water layer

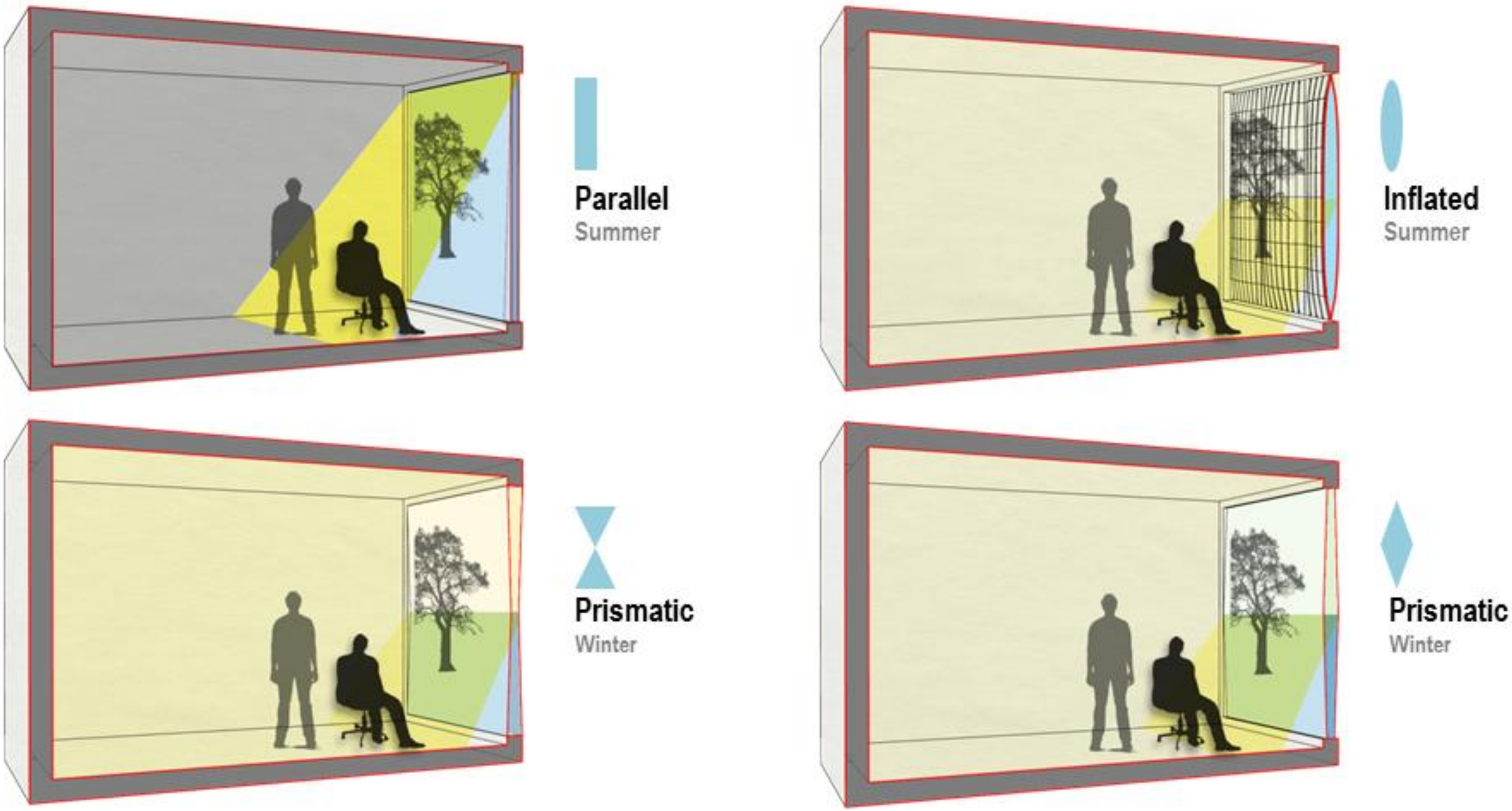


Based on the Snell's law, the driving idea of this research using the water layer as a shade (shading without shades) to block the specific angles of incident sunlight.

Regarding to total internal refraction phenomena in water (as dielectric material with refraction index of 1.33), the sunlight radiation travelled through the water layer is blocked on the tilted pane and refracting inside the water.

Shading without Shader

Controlling the light distribution through water layer



Using inner cavity in multilayer ETFE cushion as an adaptive fluid lens to adjust the light distribution; the internal refraction phenomena in water cavity in a multilayer ETFE cushion and blocking the summer high angle solar radiation while allowing the winter low angle radiation

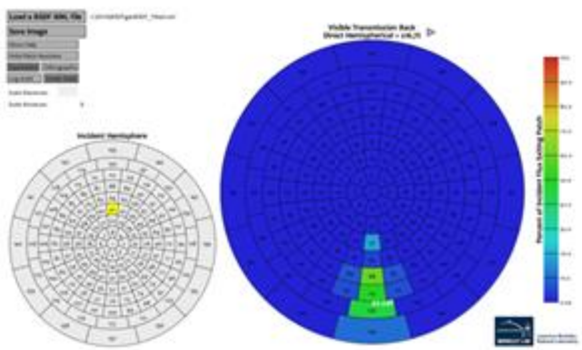
Transsolar academy

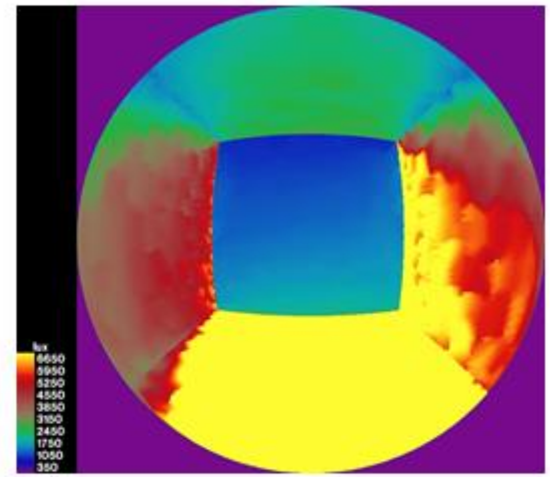
Static Daylight Simulation

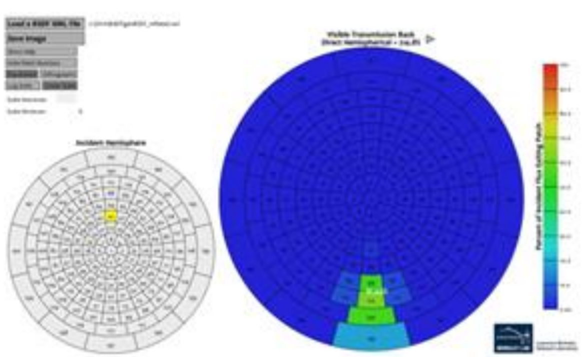
BSDF Matrix

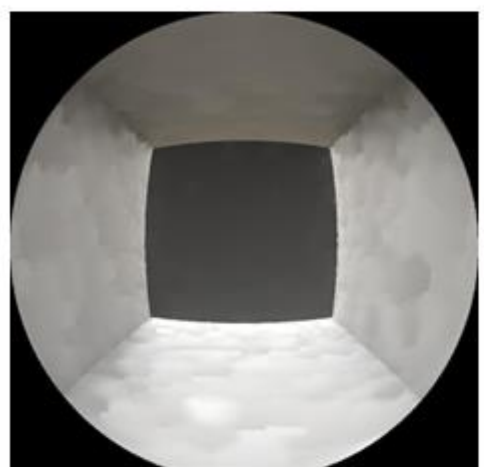
21st December

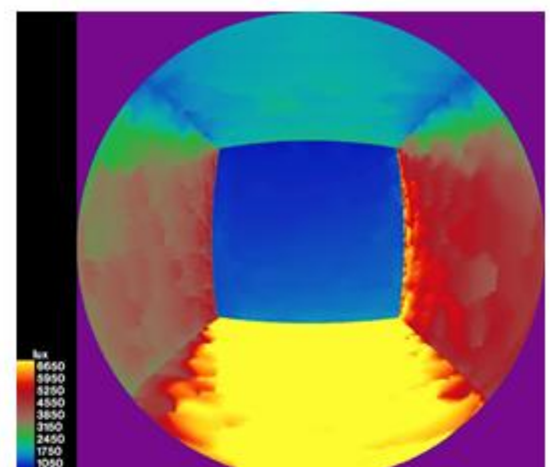
Tilted











Inflated

Lighting simulation results: The idea of redirecting light by water layer needs further researches to be done to study the effect of shape to adjust the geometry and distribute sunlight effectively. The impact of some of these shapes of water layer on light transmission and distribution have been evaluated by complex fenestration system modeling method and generating the BSDF matrices through simulating daylight by use of Optics6, LBNL Windows, Daysim and Trnsys18 new features.

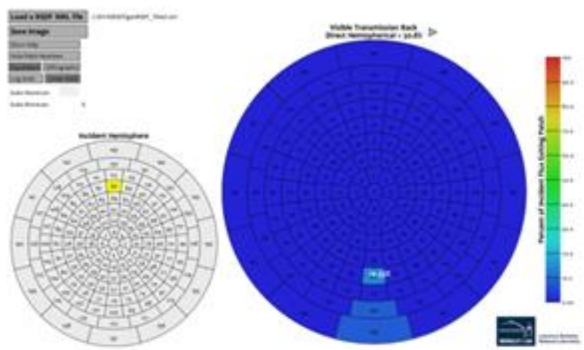
Static Daylight Simulation

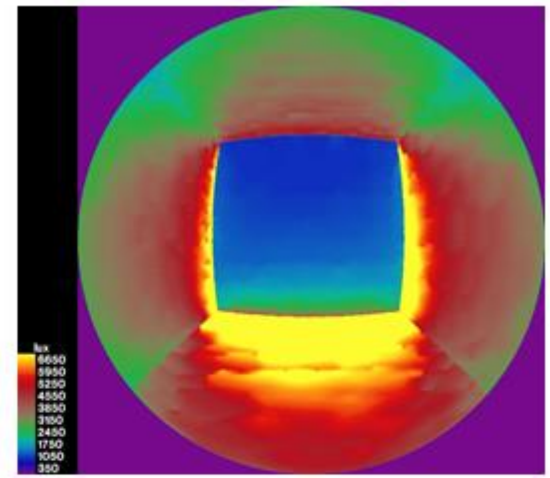
BSDF Matrix

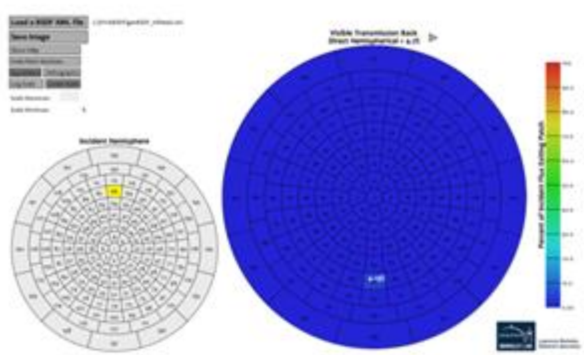
21st June

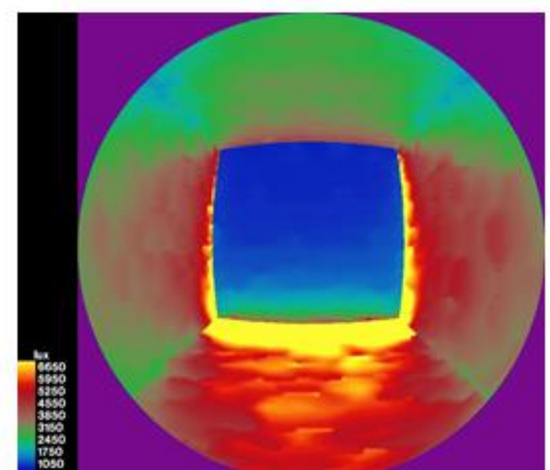
For a standard office room in Tehran and Stuttgart with a fully glazed south oriented fa ade, while the illuminance level and light distribution is in acceptable range; regarding to radiation values, decreasing the g-value of the glazing, the energy demand for cooling can be reduced potentially due to the internal refraction in water layer.

Tilted









Inflated

Water filled ETFE cushion façade

Performative Pattern Generation

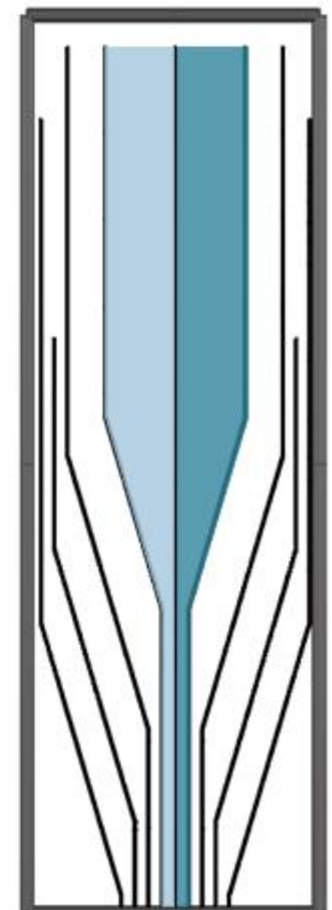
- **Supporting the ETFE foils with welded fibers**
- **Decreasing the hydrostatic pressure based on the Venturi effect**

Insert View of Façade Component

21st June

21st March

21st December



Venturi Effect & Water Circulation

Supporting the hydrostatic pressure of water in lower part of cushion, higher air pressure (the maximum pressure of 2000 pa or 0.29 psi) or the secondary support with tensile fibers or kind of cable net is necessary to avoid the foils from any plastic deformation. Supporting the ETFE foil with high performance fiberglass and carbon fibers is part of some pioneering research projects in ITKE and ICD institutes in Stuttgart (Doerstelmann, M. et al., 2015). According to the idea of Urban Algae Folly project for EXPO Milano 2015, another solution is dividing the spans into smaller clear height up to 40cm (1.31 ft). Since the water bladder is enveloped with the outer air cavities and hydrostatic pressure due to the 40 cm (1.31 ft) height of water column is about 4000 pa (0.58 psi), the resultant pressure exposed to the foil could be kept less than 2000 pa (0.29 psi). Therefore, it is possible to carry the water inside the ETFE bladders.

ACKNOWLEDGEMENTS

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